ADVANCES IN X-RAY SIMULATOR TECHNOLOGY

W. J. Summa, R. L. Gullickson, M. P. Hebert, J. E. Rowley, Defense Nuclear Agency; J.F. Leon, Centre d'Etudes de Gramat; I. Vitkovitsky, Logicon RDA

INTRODUCTION

DNA's future x-ray simulators are based upon inductive energy storage, a technology which offers the promise of more compact and affordable energy storage and delivery for larger systems. DECADE is a prime example of this technology. DECADE will store approximately 10 megajoules and deliver about 2 megajoules to separate bremsstrahlung sources or to a combined plasma radiation source load. Two DECADE prototype modules have already operated, demonstrating that key parameters can be met.

Figure 1 shows the concept of inductive energy storage. An opening switch is placed in parallel with the load. Energy is delivered to the load when the switch rapidly increases its resistance (i.e., opens). The most commonly used form is the plasma opening switch (POS) which opens as plasma charge carriers are depleted or move out of the conduction region under the influence of JxB forces. The figure also illustrates the scaling of the voltage produced across the switch. It is proportional to the current and inversely proportional to the opening time. Switch performance has been demonstrated with short opening times and lower switch voltages. The state of switch technology is also indicated in Figure 1. The risk of switch performance would be lower for soft x-ray simulators if plasma radiation source loads can operate with longer implosion times.

Plasma Opening Switches

Characteristics of opening switches determine how the simulators are designed. The key characteristics of the plasma opening switch (POS) are the conducting state of the switch when the inductor is being charged by the current source (the closed state); the rate of increase of the switch resistance and the electric field that can be supported by this resistance (the open state); and the switch jitter time, i.e., the degree of reproducibility of the rate of increase of the resistance.

The limiting factors that are associated with POS application to simulators are the 1) plasma density and volume which determines the conduction time, 2) switch resistance which determines the maximum output voltage of POS-operated inductive system, and 3) switch-to-switch reproducibility when used to combine outputs of several modules.

Figure 1 demonstrates how the increase in the switch conduction time reduces the complexity of the simulator power train. With short conduction time switches the vacuum inductor is charged by a pulse line with a few tens of nanosecond transit time (Figure 2a), rather than directly from the primary storage system. Some of the pulsers that have used short conduction switches are Gamble II, Black Jack 5, Phoenix, and PITHON, achieving output power multiplication, relative to the output without the inductive stage, of about a factor of 2.

As the conduction time increases to hundreds of nanoseconds, obtained by injecting more plasma for a given current, the pulse line can be eliminated. However, a transfer capacitor is still needed to match the output time of the Marx generator to the conduction time of the switch. This approach (Figure 3b) has been utilized in the latest generation of simulators, i.e., ZFX[1] at NRL and DECADE,[2] now under construction, and in simulator designs, e.g., in early JUPITER IES design,[3] discussed below.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUL 1995**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Advances In X-Ray Simulator Technology**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Defense Nuclear Agency**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

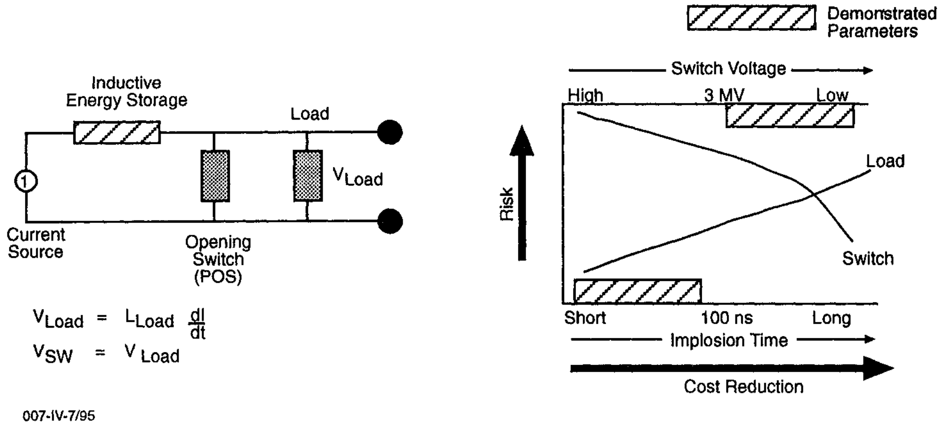

Figure 1. (Left) Schematic of the ideal inductive energy storage (IES) circuit and voltage scaling. (Right) An illustration of IES technology status applied to plasma radiation loads, described in terms of development risk and cost dependence on switch voltage and the implosion time of the plasma load.

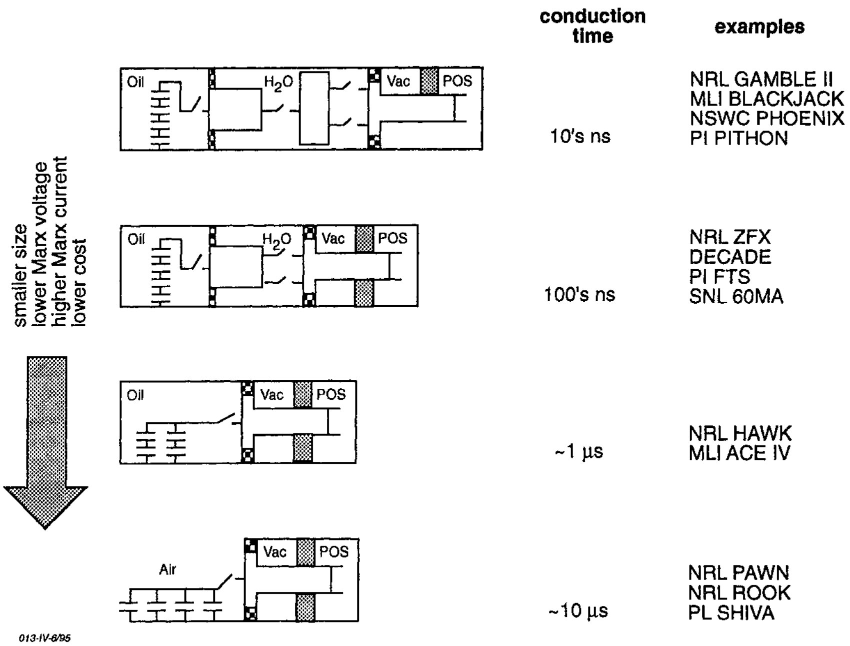

Figure 2. Circuit schematics of IES systems. Increased opening switch capability simplifies the IES pulsers and provides increasingly more practical advantages.

Finally, testing is underway to validate designs that would allow charging of the inductor directly from the capacitor bank current source (Figure 2c and 2d). In these designs, the transfer capacitor can be eliminated because the conduction time of the switch is similar to the output time of the Marx. For microsecond conduction time switches, this can be achieved using low inductance banks operating in the Marx generator configuration (Figure 2c), in order to obtain the voltage necessary to drive multi-megampere currents, associated with simulator requirements, through the inductor. Examples of this technology are the Naval Research Laboratory Hawk device[4] and the Maxwell Laboratories ACE IV.[5]

An alternative method to POS switching that is capable of providing much longer switching times is also under consideration. It utilizes various versions of the plasma flow switch.[6] Because plasma flow switching extends the conduction time to several microseconds, source voltages needed to drive the

current through the inductor could be below 100 kV, so that capacitor bank can operate in air (Figure 2d). The plasma flow switch concepts are being developed at PL Shiva facility and at Los Alamos in the Athena program.

Configurations for IES Systems

The modular design, such as that used for DECADE, is only one of many possible configurations for an inductive energy storage system. DECADE, developed by Physics International Corporation for DNA, employs 16 separate modules. Each of these includes an energy storage unit, a transfer capacitor, an inductor, and a plasma erosion opening switch. This design is represented by the schematic of Figure 2b, with details described below.

Other designs take advantage of improvements in opening switch performance by eliminating the transfer capacitor to arrive at a more compact and simpler (e.g. fewer parts) design. The ACE 4 IES system[5] employs a single microsecond-long conduction time triple-disc configuration opening switch fed by a single triplate transmission line to arrive at a more compact design. (A somewhat higher inductance version of ACE4 system, using coaxial switch has also been tested at Maxwell Laboratories.[7])

GIT-16, now operating as GIT-8(using one-half of the primary storage of the GIT-16[8]), at the Institute for High Current Electronics in Tomsk also operates without a transfer capacitor but uses a modular design to connect the energy storage units to a single central switch. SYRINX, a proposed design to be built by the Centre d'Etudes de Gramat (CEG) in France would employ a modular approach, possibly with a separate longer conduction time plasma erosion opening switch to store 10-20 MJ.

Finally, one of two proposals for the Sandia National Laboratories — Defense Nuclear Agency (DNA) Jupiter concept employs 60 modular switches and transfer capacitors in a design superficially similar to DECADE. The second proposal, based upon the Inductive Voltage Adder (IVA) concept, would use 30 IVA modules.

Parameters for each of these designs are compared in Table 1. The numbers in parenthesis are actually achieved values.

Table 1. Parameters for Inductive Energy Storage Simulator Concepts

Simulator/ Parameter	Stored Energy, MJ	Peak Current, MA	Number of Modules	Switch Conduction Time, ns	Status
DECADE	10	25	16	300	one module operating
ACE 4	4 (2)	10 (3)	1	1600 (1000)	operating
SYRINX	10 (1.7)	20 (7.6)		1000 (860)	MAG 3 in design
GIT 16	4.8 (2.4)	10 (4)	16 (8)	1000(1000)	GIT 4 & 8 operating
Jupiter IES	135	66	60	680	design
Jupiter IVA	94	60	30	N/A	design

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DECADE PROGRAM

In the 1980's DNA's pulsed power R&D program took a new direction to develop a more efficient large x-ray simulator. The performance goal was to be an order of magnitude improvement over existing hard x-ray testing capability which was at that time roughly 20 kRad (Si) at 2:1 uniformity over 1000 cm^2 To achieve this goal (20 kRad (Si) at 2:1 uniformity over 10,000 cm^2) affordably, DNA proposed that this next simulator be based on inductive energy storage (IES) technology. This simulator was planned to be

an intermediate step in reaching a full threat x-ray simulation capability, which was believed to be reachable in an affordable way only through an IES approach. The DECADE concept is illustrated in Figure 3.

Two possible machine concepts grew out of that DNA program: a modular machine employing transfer capacitors developed by Physics International (PI), and a "monolithic" design with a single large switch by Maxwell Laboratories.

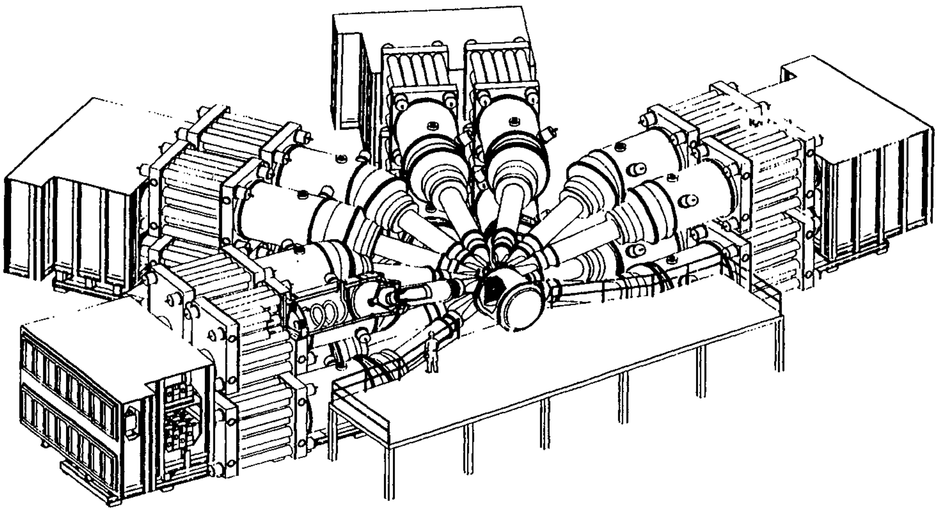

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Figure 3. DECADE Simulator Assembly and Test Chamber

The PI approach began with EYESS, a pure IES testbed with a coaxial transmission line geometry and 1/3 MJ stored energy. The performance of an EYESS-driven bremsstrahlung diode looked promising and the machine design was consequently scaled up by a factor of three in stored energy. This larger design was realized in FALCON, with 1 MJ of stored Marx energy. At this time plans for DNA's next machine began to take on added definition. PI's concept for this machine, to be called DECADE, was modular and consisted of eight FALCONs.

FALCON's scaling was limited by switch performance. FALCON, still purely IES, was characterized by a quarter cycle rise time of approximately 1 microsecond. However, FALCON's plasma opening switch (POS), achieved conduction times of 400ns at best before opening, and as a result F ALCON's load voltage was inadequate for bremsstrahlung diode purposes.

At this point PI decided on a hybrid approach. EYESS's configuration downstream of the Marx was modified to include a water-filled transfer capacitor. In this approach the larger and slower Marx charged the low inductance transfer capacitor, which was then coupled into the downstream IES transmission line via low jitter gas-filled switches. The PI DECADE concept was modified to consist of 24 hybrid EYESSs. An analysis of the cost of this DECADE showed that the principal hardware expense originated in the number of transfer capacitors, and not their intrinsic size. PI's DECADE design was then adjusted to consist of 16 modules each sized more or less midway between EYESS and FALCON, or at 0.5 MJ stored Marx energy.

As PI's DECADE design took on added definition and folded in other constraints, such as machine footprint, PI elected to incorporate a planar POS feeding into a linear diode. The planar switch failed to perform and the design reverted to a coaxial switch with a downstream transition into planar geometry. In addition, conduction time limits suffered also by the coaxial switch, necessitated an adjustment to the configuration and the electrical properties of the output bus leading from the transfer capacitor into the transmission line upstream of the POS.

POS voltage performance in this latest design, however, failed to meet expectations. Adjustments to switch configuration (reduced cathode radius) and implementation of gun plasma sources, as opposed to flashboards, did bring POS performance up to levels necessary to drive bremsstrahlung radiation sources.

Operation at adequate POS voltages uncovered yet another technical hurdle, which is perhaps fundamental to IES in practical implementations: power flow. Plasma in the magnetically insulated transmission line between the POS and the radiation source load, having evolved in some manner from the switch region, shunted the opened voltage, and the loss of energy integrated over the length of the transmission line was nearly total.

PI addressed this problem straightforwardly, by minimizing the length of transmission line between the switch and the bremsstrahlung diode. This involved finding the optimal balance between the contamination of the diode with switch plasma, i.e., placing the switch too close to the diode, and increased transmission line losses, i.e., placing the switch too far from the load. This balance was reached after a long empirical convergence process. In addition, this solution necessitated reverting to a circular diode.

This final adjustment was the last major configuration change to PI's design. Since then PI has continued to make second order changes to the design, as programmatic constraints permitted, in order to enhance the performance of each DECADE module from an operational point of view. These principally focused on improving reliability and reproducibility.

At present, the DECADE module engineering test bed at PI, called DM1, driving a bremsstrahlung diode load has demonstrated typical POS conduction times and currents of 280ns and 1MA, respectively, and typically opens to 2MV. DM1 has demonstrated 8ns of radiation output jitter over a 20 shot qualification test sequence.

DECADE still faces many technical challenges. The most conspicuous derives from the fact that DECADE's predicted performance, driving a large area array of bremsstrahlung diodes, falls short of the original overall performance goal of 20 kRad (Si) over 10,000 cm^2 by a factor of two. In addition, DECADE faces unique challenges such as synchronization and spatial uniformity of radiation from the anode converter, caused by the modularity of the machine and its radiation source. The final characteristics of such a radiation source, and therefore the ultimate performance required of each DECADE module, will not be completely known until the testing of DECADE's first quadrant, which is scheduled to occur in 1996.

ACE-4 TEST BED

The ACE 4 concept, invented by Maxwell Laboratories, Inc., originated as one of two competing designs for DECADE. ACE 4 is a compact system storing 4MJ which directly drives a double disc radial plasma opening switch[5] (or a coaxial plasma switch[7]) from the Marx generator without the use of a transfer capacitor.[5] This requires a switch conduction time of about 1 microsecond for efficient operation. ACE 4 is designed to deliver 8MA in 1.6 μs to the radial plasma opening switch. ACE 4 is illustrated in Figure 4.

ACE 4 uses 24 sub-Marxes organized in four oil tanks which drive multiple parallel plate transmission lines. The transmission lines connect to a load coupler using two parallel oil-vacuum interfaces. Each oil-vacuum interface couples to one of two back-to-back large area plasma opening switches. These can drive a plasma radiation source or electron beam load.

As with the other IES concepts described in this paper, the key issue for enhancing performance is the POS. Efforts to improve the ACE 4 POS are based upon the concept that hydrodynamic effects dominate during the conduction phase. The switch opens as magnetic JxB forces move the plasma out of the conduction gap, resulting in lower plasma densities at opening time.

ACE 4 POS performance is being optimized using large area slow plasma flashboard sources producing a peak density of 2-5x10^{15} cm^{-3}. This density is reproducible within 10%. Present performance with this slow flashboard produces conduction times of about 1 μs with POS voltages of about 300 kV.

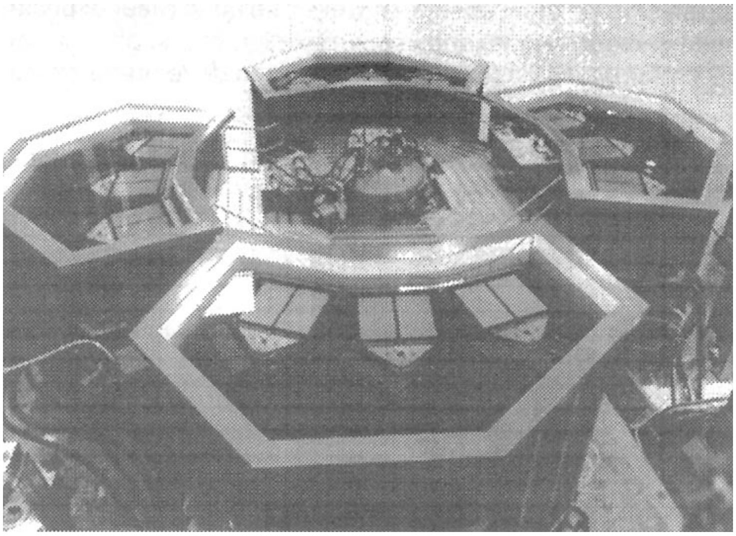

Figure 4. ACE 4 Inductive Energy Storage Test Bed

This performance is not yet optimized and appears to be limited by plasma motion downstream of the switch region, with insufficient thinning of the density before leaving the POS region.

Table 2 summarizes the design parameters of ACE4 and measured values obtained in experiments where ACE 4 is used to drive plasma implosion loads.

Table 2. ACE 4 Characteristics

Parameter	Value
Design Values	
Stored Energy (MJ)	4.6
Peak Current (MA) to the POS	8 in 1.6μs
Output Voltage (MV)	2
Number of Switches	1 doubled sided
Number of Marxes	24 sub-marxes in four oil tanks
Measured Performance Values	
Stored Energy (MJ)	2
Switch conduction time (μs)	1.2
Current transferred to load (MA)	3.5
Output voltage (MV)	0.4
Energy transferred to load	108 kJ (PRS load)

GIT-16 GENERATOR

GIT 16 is a pulse power generator of the High Current Electronics Institute (HCEI) in Tomsk, Russia. It is based upon the concept of directly driving the opening switch from the Marx bank. However, the Marx banks and coaxial radial transmission lines are modular. As in the case of ACE 4, this single opening switch drives an imploding PRS load. GIT-16 is projected to store about 4.8 MJ at 840 kV in a capacitor bank consisting of parallel modules containing lower voltage capacitors connected in series.

GIT-16 is being developed in stages. The first stage is designated GIT-4 and contains one quarter of the parallel modules. GIT-4 is being used to study the opening switch, as well as perform implosion experiments. It is one of the first major system to test the performance of an inductive system as a current source for a PRS load. At this time, one half of the modules has been assembled; the assembled configuration is called GIT-8.

The GIT series of generators uses capacitor blocks consisting of four series elements of 4.8 μF resulting in a 1.2 μF, 70 kV unit, which is assembled into a module consisting of 12 units (0.1 μF) with peak charging voltage of 840 kV. Four of these are used in parallel to configure one Marx bank with a capacitance of 0.4 F. Nine such Marx banks, with a capacitance of 3.6μF, form the GIT-4 system. The stored energy of GIT-4 is 1.2 MJ. Further addition of modules is planned for GIT-16 generator, shown in Figure 5.

GIT-4 was tested as a driver for PRS designs developed to improve implosion stability and optimize the radiation yields.[9] It uses a plasma opening switch which consists of 32 plasma guns (20 cm long rods) or flashboards (with 32 chains) producing a density of approximately 10^{14}cm^{-3}, with the flashboard located 7 cm behind the anode. The current in the guns is the same as in the chains. The load is operated by injecting up to three concentric gas puffs into the diode region. An option to preionize the gas is available. Operating most of the experiments at 50 kV charge, switch current of 2.1 MA has been obtained, with charging time of about 1μs. Current transfer (defined as ratio of the peak load current to the peak POS current) is 70%. Typical implosion times were 160-200 ns. While various stabilizing factors were observed in these experiments, there appeared some warning signs that the PRS/POS interaction may degrade the PRS performance and that other switch and load concepts may be needed to utilize systems such as GIT-16 most efficiently for production of soft x-rays.

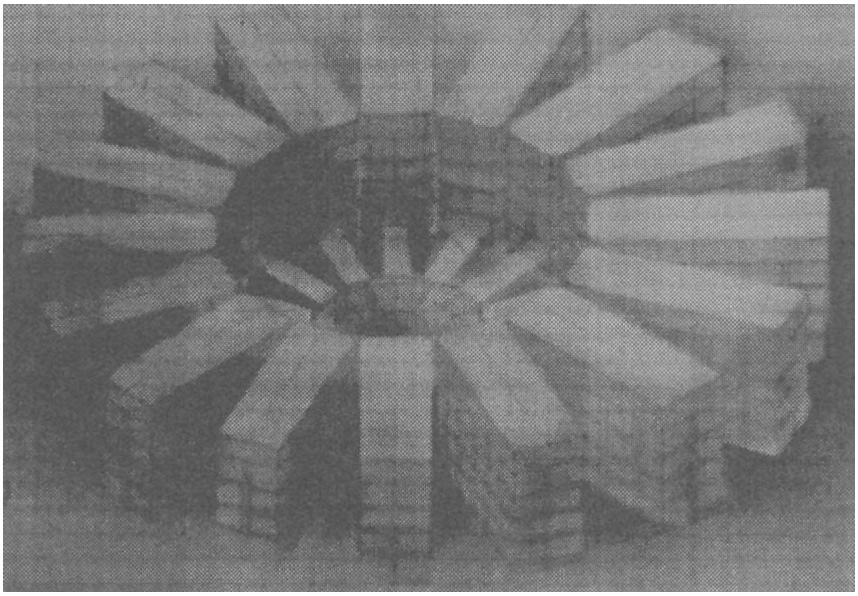

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Figure 5. Planned GIT-16 IES system at High Current Electronics Institute

SYRINX CONCEPT AND DEVELOPMENT

A new X-ray simulator based on inductive energy storage is under consideration in France. This simulator, called SYRINX, would be built at the Centre d' Etudes de Gramat (CEG). It would employ a modular.long conduction time current source to drive a PRS load. SYRINX is planned to be in the 10-20 MJ stored energy range and is to deliver 20-30 MA to a PRS load making it comparable to DECADE in terms of stored energy and current into the load. No decision to build SYRINX will be made until the affordability of the IES concept is demonstrated in sub-scale technology demonstrations. Affordability is defined to be <$1.5/J of stored energy.

SYRINX will employ modular primary energy storage technology with some novel features, such as fast multichannel switches in the Marx bank. This will allow it to drive a POS switch directly from the bank, without needing the transfer capacitor or pulse line for current rise time compression, as is done, for example, in DECADE. Nevertheless, an option to that scheme is considered. The option consist in adding a passive transmission line between the Marx and the vacuum interface. Because the Marx used in the

design is fast (quarter cycle into a short circuit is 650 ns) the use of a transmission line between the Marx and the vacuum interface will have the following consequences:

- 75% of the stored energy will be injected into the vacuum storage inductance, with a rise time of the current into the POS of 800 ns;
- Marx generator will be protected from reversal and will allow use of high energy density capacitors;
- It will mechanically decouple Marx banks from the vacuum section.

As a result, this scheme may lead to a more compact and overall less expensive design, despite the need of an additional passive component.

The POS switch in the SYRINX will be downstream of the convolute, which converts the triplate system to coaxial electrode system at the oil-vacuum interface. The coaxial MITLs are used to converge the power, via a vacuum convolute, to the PRS load. A bremsstrahlung load version is also contemplated with additional opening switches to sharpen the rise time.

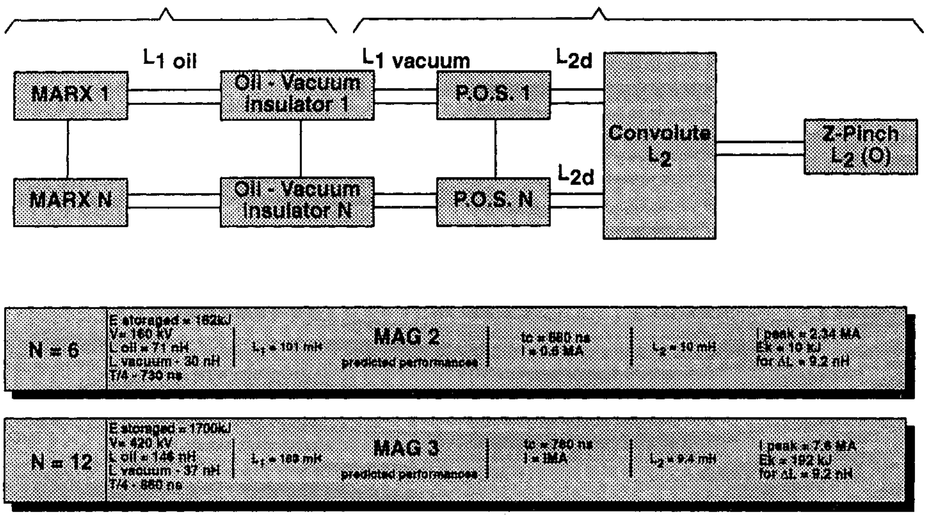

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Figure 6. Multimodule IES Concept

The modular approach used in the SYRINX concept allows testing of prototype modules. MAG-1 is operating now as a test bed for the fast MARX generator and POS technology. CEG is now fabricating the smaller MAG-2 module for evaluation starting in 1995. Three to five years later, it is expected that a larger MAG-3 module will be on line for testing the critical technology areas. Parameters of the prototype modules are given in Table 3.

Table 3. SYRINX Parameters

Parameters	MAG 1	MAG 2	MAG 3	SYRINX
First Operation	Operating	1995	1998?	?
Number of Parallel Modules	1	6	12	?
Total Energy (MJ)	.007	0.162	1.7	10-20
Energy per Module (MJ)	.007	0.027	0.142	?
Total Current (MA)	0.500	2.3	7.6	30?
Current per Module (MA)	0.500	0.6	1.0	?
Conduction Time (ns)	600	730	860	900?
Output Voltage (kV)	70	160	420	1000

The final SYRINX design is not yet determined. Figure 6 illustrates the multi-module IES concept that is the basis for SYRINX and compares MAG 2 and MAG 3. MAG-2 modules will be configured in a radial six-spoke system, as shown in Figure 7.

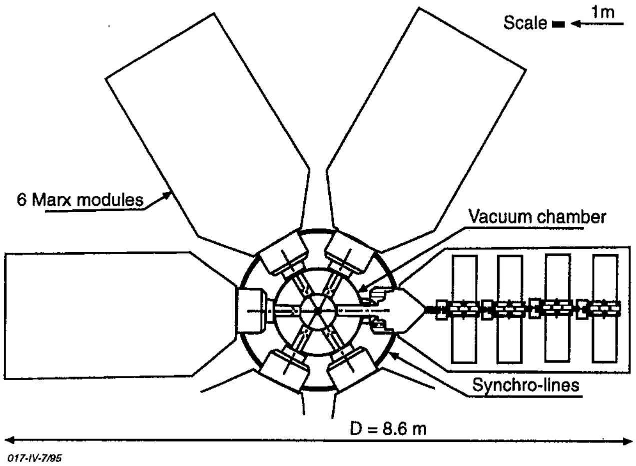

Figure 7. Top view of MAG 2 prototype

JUPITER DESIGN CONCEPT

Jupiter is a proposed Sandia National Laboratories — Defense Nuclear Agency "next generation" x-ray simulator designed to deliver 15 MJ to a plasma radiation source load with a current of at least 60 MA.[3] Designs for two promising approaches were developed by the Jupiter Design Options Study Team: (1) a 60 module IES system storing 135 MJ using 0.7 us conduction time plasma erosion opening switches and (2) a 30 module Inductive Voltage Adder based upon Hermes III technology at SNL storing 94 MJ.[10]

One noteworthy result of the JDOST process was the development of a new, modular IES concept. This concept, although superficially similar to DECADE, provides substantial innovation in comparison by eliminating the DECADE large transfer capacitor and output line and replacing them with a small, passive (i.e. not switched) water-pulse forming section for each module. This results in a substantially more compact design. The modular IES design is shown in Figure 8.

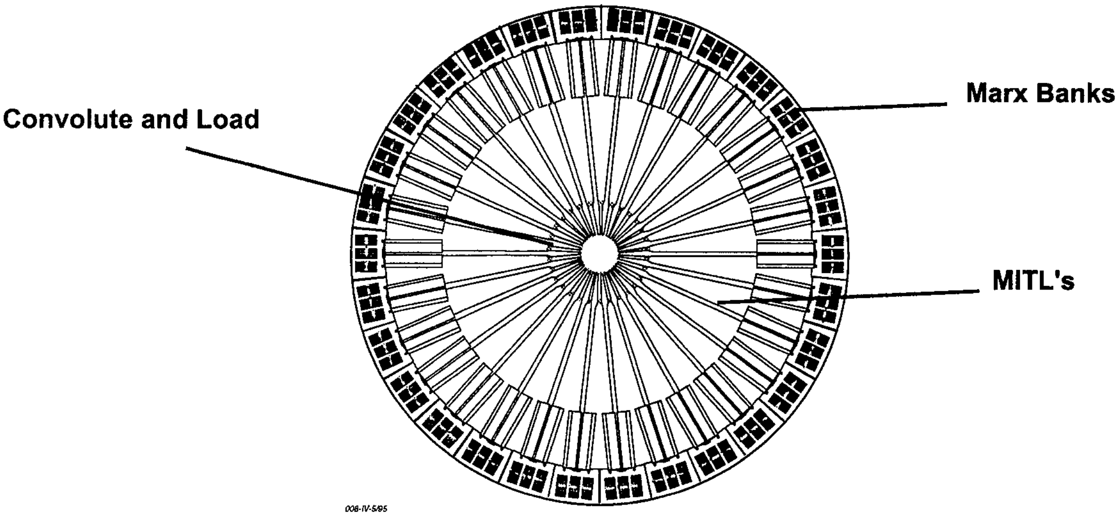

Figure 8. Inductive Energy Storage Jupiter Design Concept

In this approach 135 MJ is stored initially in Marx banks. Each module has six Marx generators in parallel. The Marxes feed a single, long (15m) coaxial storage inductor. A 680 ns POS acts as the switching element at the end of the storage inductor. The output of the modules are convoluted to form a central disk feed (single or double triplate). A post-hole convolute couples the current to the plasma radiation source load.

Parameters for the Jupiter IES concept are compared with DECADE in Table 4.

Table 4. Inductive Energy Storage Jupiter Design Comparison with DECADE

Parameter	Jupiter	DECADE
Number of Modules	60	16
Module Voltage (MV)	8	2
Module Current (MA)	1.1	1.5
Module Power (TW)	9	3
POS conduction time (ns)	680	300
Oil marxes per module	6	6
MITL length (m)	15	5
Stored Energy (MJ) at 90 kV charge	135	9.2

The reader should conclude from this comparison that a Jupiter IES module does not represent a substantial extrapolation over DECADE performance with, however, one significant exception. This exception is the conduction time of POS (680ns) and the increases in module power and voltage that accompany the larger current and faster opening. We are still striving for reliable, efficient, and predictable performance from the 300 ns DECADE POS. The technical risk associated with POS performance was the primary area of concern expressed by the JDOST with regard to this concept.

The Inductive Voltage Adder design is based on the Hermes III gamma ray simulator at Sandia National Laboratories in Albuquerque, NM. Hermes III uses water pulse forming technology and laser-triggered gas switches to deliver electrical power to a 1 MV, 0.8 TW cavity. Twenty such cavities are stacked in series to achieve the desired 20 MV in Hermes III in a single module. The cavities are inductively isolated from one another and switched to add the voltages in series using Metglass cores. A long magnetically insulated transmission line (MITL) delivers the energy to the load.

In the Jupiter IVA design, the cavity voltage is increased to 2 MV, the cavity power is increased by a factor of 5 to 4 TW, and there are four cavities per module. This design stores an energy of 94 MJ at 95 kV Marx charging voltage. Each cavity is driven by four water pulse forming lines, two water intermediate storage capacitors, and one oil-insulated Marx. The pulsed power is transmitted through 30 long (13 m) vacuum MITLs that are convoluted together to form a central disk feed. The central disk feed converges the current radially to a post-hole convolute.

The Jupiter IVA design is shown in Figure 9 and compared with Hermes III in Table 5.

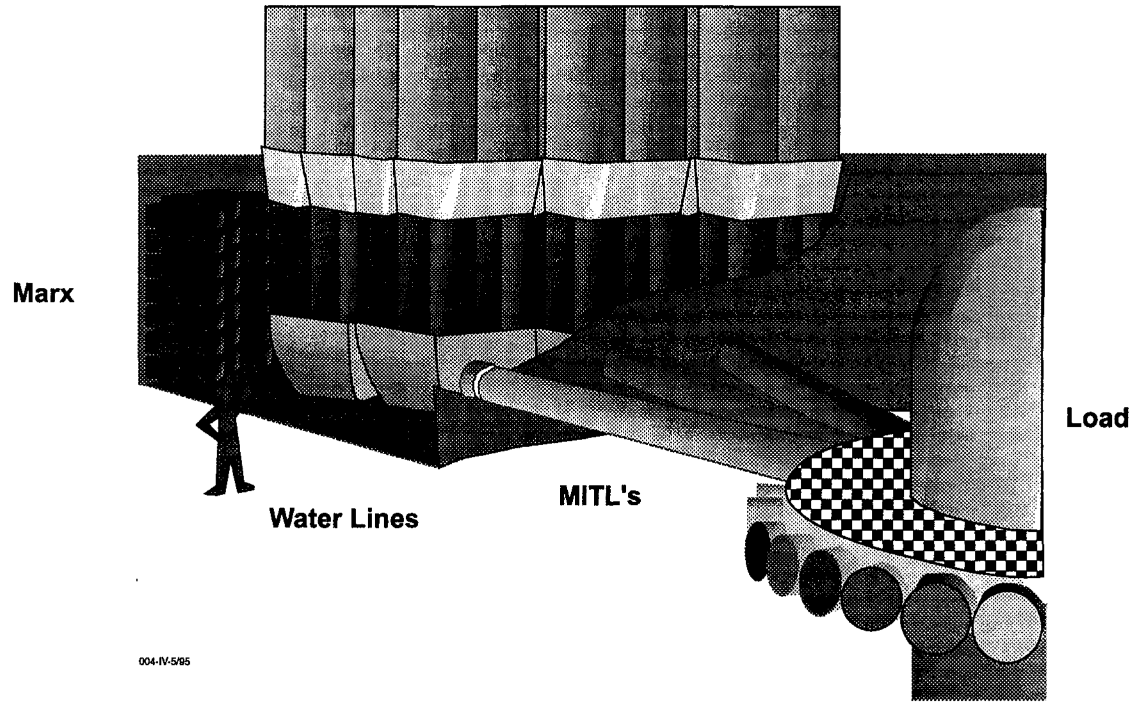

Figure 9. Jupiter Inductive Voltage Adder Design Concept

Table 5. Jupiter IVA - Hermes III Parameter Comparison

Parameter	Jupiter IVA	DECADE
Number of Modules	30	1
Module Voltage (MV)	8	20
Module Current (MA)	2	0.8
Cavities per module	4	20
Cavity Voltage (MV)	2	1
Cavity Power (TW)	4	0.8
Water PFLs per cavity	2	1
Water intermediate stores per cavity	2	1
Oil marxes per cavity	1	1
MITL length (m)	13	7
Stored Energy (MJ) at 95 kV charge	94	1.5

The reader is invited to note that the extrapolation beyond current Hermes III technology is not great, presumably resulting in an acceptable risk for this design approach. The primary area of concern expressed by the JDOST for this design was affordability based upon the large parts count.

SUMMARY

Inductive Energy Storage technology represents an affordable approach to the design of large x-ray simulators if opening switches can be made to perform reliably and efficiently. A variety of innovative designs are available for the development of the next U.S. simulator beyond DECADE and for other nation's future large x-ray simulators. Inductive voltage adder technology provides a competitive and moderate risk approach for large x-ray simulators. Research programs conducted by SNL, NRL, and DNA and supporting contractors should identify which areas of parameter space are most favorable for each of these concepts.

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